FATE OF THE CHICXULUB IMPACTOR P.H. Schultz and S. Sugita. Geological Sciences, Box 1846, Brown University, Providence, RI 02912.

Abstract: The fate of the impactor during hypervelocity impacts has implications for the geographic dispersal and arrival times of cosmic signatures in the terrestrial record (e.g., the global Ir component at the K/T boundary versus siderophile depleted impact melts). During oblique impacts, all three phases (vapor, melt, solids) of the impactor are produced even at hypervelocities. Each phase, however, exhibits different patterns of dispersal that can affect not only the dissemination of the impactor but also the crater excavation process possibly relevant to the Chicxulub impact.

Introduction: Laboratory experiments at the NASA Ames Vertical Gun Range allow monitoring the evolution of different phases (fragment, melt, vapor) of the impactor using spectroscopy, high-speed imaging, downrange witness foils, and plate-out surfaces. Such experiments reveal consistent phenomena that relate to the fate of different portions of the impactor as it penetrates the target. The vapor phase is largely derived from the lower portion of the impactor during penetration. In oblique impacts, this component mixes with the target along the interface at reduced temperatures (relative to a vertical impact). Significant fractions of the impactor, however, do not undergo vaporization or melting initially. At very low impact angles (< 15°), the projectile survives impact and decouples from the cratering process. At modest impact angles (15°-45°), however, surviving debris erode the target surface downrange prior to the excavation crater. The pattern of impactor effects, dispersal, and arrival time could hold clues for the angle of the Chicxulub impact (1).

Approach: Hypervelocity impacts in the laboratory cannot generate the degree of vaporization expected on planetary surfaces because of limitation in impact velocities. Nevertheless, impact velocities on asteroids are comparable to laboratory conditions (5 km/s) and choices of impactors can provide a surrogate for assessing the process at higher velocities (e.g., cadmium, polyethylene, copper). The purpose here is to assess the fate of the impactor, i.e., where it is and what it is (solid, melt, vapor).

High-speed spectroscopy allows probing different portions of impact-generated vapor through time (2, 3). Use of Pyrex, stainless steel, and aluminum allows tracing the impactor through rapid chemical reactions of vapor with anhydrite and carbonate targets (dolomite). Aluminum impactors produce extremely luminous AlO identified spectroscopically and allows tracing impactor vapor by-products in high-speed imaging (1 to 4 µs time intervals). Rather than being thoroughly dispersed through the vapor cloud, this vaporized impactor component lines the outer portion of an expanding thin shell of target vapor as it moves downrange. For a 30° impact angle, the combined expansion and downrange translation results in a net velocity (4-5 km/s) less than the initial impact velocity (5.5 km/s). Because the vapor component expands as it moves downrange, the self-luminous shell appears to be hinged uprange near the impact point in oblique impacts into solid targets (< 60° from the horizontal). High-speed spectroscopy reveals absorption lines from cooled impactor vapor (Na in the case of Pyrex) that has expanded in advance of a thermal background uprange from the first point of contact. Downrange, emission lines from the impactor become more pronounced after 5 µs. These lines (AlO, Na, and K for Pyrex; AlO for aluminum) weaken with time but can persist well beyond 100 µs as the vapor cloud continues expanding. In general, the ratio of impactor to target emission line intensities indicates that the impactor signature increases as impact angle decreases (60° versus 30_), perhaps as a result of less masking by the target component or multiple impacts by impactor ricochet and shear heating at lower angles (2).

Witness plates downrange allow assessing the size, physical state (melt versus solid), and trajectory (velocity and angle) of impactor products (4). New experiments using thin aluminum foil, however, preserves the fragment size and shape distribution provided that the foil thickness remains a small fraction of the fragment size. The physical state of the debris is inferred from the presence or absence of associated melt droplets and the effect of the witness foil on further dispersal on a secondary foil behind the leading foil. The trajectory was assessed not only by the pattern of fragments but also by high-speed imaging of their arrival at the witness foils. Isolation of the impactor from the target debris was accomplished by using small water targets. Aluminum, quartz, Pyrex, and Lexan impactors in order to assess survival patterns depending on different material properties.

Results demonstrate that the lower temperature melt and clastics from the impactor follow a different trajectory from the vapor phases. Molten debris arrives first with low trajectories at velocities (8 km/s) exceeding the initial impactor

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velocity (5.5 km/s). The later arriving components reflect the specific style of impactor failure (catastrophic disruption, spallation, shear). The downrange impactor spray forms a fan substending an angle about twice the impact angle about twice the impact angle (from the horizontal) when $\delta_p v_\theta^2$ >> yield strength of the impactor (v_θ = vsinθ). Such a pattern is consistent with the combined effects of outward expansion due to catastrophic disruption (proportional to vsinθ) and retained downrange motion (proportional to vcosθ). Nevertheless, spall fragments also occur generally on line with the trajectory. When the jetting was isolated from the debris, however, it exhibited a velocity more consistent with theory (5, 6). At lower impact velocities or lower angles increasing portions of the impactor undergo simple shear. Catastrophic impactor disruption also can be mitigated by impact into a lower impedence veneer over the target. Impactor debris appears to interfere with the development of the idealized jetting process.

Use of easily vaporized impactors (Lexan and cadmium) not only produced similar patterns of impactor failure but also plated out impactor material on the downrange target surface. The sequence and pattern of plating underscore the concept of decoupling of early-stage impact processes and downward (as well as upward) expansion of the vapor phases (1, 2).

Discussion and Implications: Such experiments demonstrate that the fate of the impactor at hypervelocities follows a well-defined pattern of fragmentation, melting, and vaporization corresponding to different stages of penetration and representing different portions of the impactor. Even easily vaporized impactors (Lexan, cadmium) providing surrogates for higher velocity events are not fully vaporized and produce significant clastic debris during oblique impacts indicative of spallation and mechanical failure (<60°). The half-angle subtended by the downrange spray of impactor debris is found to depend on the ratio of the vertical velocity component to the downrange translational motion. As impact velocities approach the shear wave velocities of the impactor, simple shear of the impactor occurs. Melt and debris produced during the earliest stages follow low trajectories and have velocities comparable to the initial impact velocity. Vaporized fractions, however, follow higher trajectories mixed with target material. Although the expansion velocity of the impactor vapor may exceed the escape velocity of many planetary bodies, its actual fate depends on its net velocity in the target frame of reference, (i.e., subtracting the downrange component of the translational motion of the cloud), rather than that of moving ballistic vapor cloud.

These observations have several implications for understanding the dispersal of the impactor in much larger planetary scale impacts. First, most of the impactor in oblique impacts decouples from the later crater-forming process and retains significant momentum from the impactor. Second, even relatively high-angle impacts can result in surviving impactor fragments dispersed in crater floor melt. Third, the vaporized impactor follows a trajectory that ensures both late arrival (downrange sub-orbital insertion) and early arrival (uprange) relative to late-stage ejecta in modest angle impacts (30°-45°). Such a sequence might account for the seemingly contradictory occurrence of Ir at the K/T boundary, e.g., above in North America (7) but below in Belize (8) for an impact trajectory from the southeast (1). Fourth, the combined effects of the lower impedance sedimentary sequences and shallow sea (<100 m) at Chicxulub should have enhanced the effects of asymmetry during the initial stages of crater formation. Fifth, molten and clastic impactor debris interact with the downrange surface prior to arrival of ballistic ejecta from the excavation stage of cratering. Byproducts from this component of melt should record a different history (temperature, viscosity, impactor fraction) relative to clast-rich melt retained within the crater.

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